ON THE DYNAMICAL AND PHYSICAL STATE OF THE 'DIFFUSE IONIZED MEDIUM' IN NEARBY SPIRAL GALAXIES

Jing Wang[1] and Timothy M. Heckman[1]

Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218

and

Matthew D. Lehnert[1]

Leiden Observatory, Postbus 9513, 2300RA, Leiden, The Netherlands

ABSTRACT

We report the initial results from a program to study the morphology, physical state, and kinematics of the 'Diffuse Ionized Medium' ('DIM') in a sample of the nearest and brightest late-type galaxies. For each of five galaxies (NGC 2403, M 81, NGC 4395, M 51, and M 101) we have analyzed deep narrow-band $H\alpha$ images of the entire star-forming disk, and long-slit spectra of the inner (~ 10 kpc) disk with a resolution of 40 to 75 km s^{-1}. We find that the DIM covers most of the star-forming disk, and is morphologically related to the presence of high-surface-brightness gas (the giant HII regions). The DIM and the giant HII regions differ systematically in their physical and dynamical state. The DIM is characterized by enhanced emission in the low-ionization forbidden lines ([OI], [NII], and [SII]), and even the high-ionization [OIII]$\lambda5007$ line is moderately strong in the DIM in at least three cases. This last result contrasts with upper limits on the [OIII] surface brightness in the local DIM of our own Galaxy (the 'Reynolds Layer'). We directly verify the inference made by Lehnert & Heckman that the DIM contributes significantly to the spatially-integrated (global) emission-line ratios measured in late-type galaxies. We also find that the DIM is more disturbed kinematically than the gas in the giant HII regions. The deconvolved (intrinsic) widths of the $H\alpha$ and [NII]$\lambda6584$ lines range from 30 to 100 km s^{-1} (FWHM) in the DIM compared to 20 to 50 km s^{-1} in the giant HII regions. The high-ionization gas in the DIM is more kinematically disturbed than the low-ionization gas: the [OIII]$\lambda5007$ lines have intrinsic widths of 70 to 150 km s^{-1}. The differing kinematics implies that 'the DIM' is not a single monolithic phase of the ISM. Instead, it may consist of a 'quiescent DIM' with a low ionization-state and small scale-height (few hundred pc) and a 'disturbed DIM' with a high ionization state and moderate scale-height (0.5 to 1 kpc). We argue that the quiescent DIM is most likely photoionized by radiation from

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O stars leaking out of giant HII regions (although this requires fine-tuning the opacity of galactic disks to ionizing radiation). The disturbed DIM is most likely heated by the mechanical energy supplied by supernovae and stellar winds. Since the disturbed DIM accounts for only a minority ($< 20\%$) of the Hα emission in the regions we have studied, there is no fundamental energetics problem with this model, but it does requires mechanically-heated gas to have a high areal covering factor in the inner disk (which needs to be confirmed observationally). We find no clear discontinuity between the physical and dynamical properties of the giant HII regions and the quiescent DIM. The quiescent DIM is morphologically related to the giant HII regions and there is a smooth dependence of the emission-line ratios and emission-line widths on the surface brightness of the emission. Thus, we suggest that a unified approach to the study of the DIM and giant HII regions in star-forming galaxies will prove fruitful.

Subject headings: ISM: structure — ISM: kinematics and dynamics — HII regions — galaxies: individual (M 51, M 81, M101, NGC 2403, NGC 4395)

1. INTRODUCTION

The interstellar medium (ISM) in our Galaxy is known to be a multi-phase complex system. The most recently-discovered major component of the ISM is the wide-spread diffuse ionized medium (Reynolds 1990, Kulkarni & Heiles 1988). This gas, usually called the 'Reynolds Layer', is characterized by a relatively low ionization state compared to normal HII regions, a low surface brightness, relatively large scale height, and substantial energetic requirements. These latter are so severe that the Reynolds Layer must either soak up nearly 100% of the mechanical energy supplied by supernovae and stellar winds or the topology of the interstellar medium must allow a substantial fraction of the ionizing radiation produced by massive stars to escape the Galactic disk and propagate to moderate scale heights. In either case, the implications for our understanding of the structure and energetics of the interstellar medium are considerable.

In several nearby normal spiral galaxies, gas with apparently similar properties to the Reynolds Layer has been found as well (see recent reviews by Dettmar 1992, Rand 1996a, Walterbos & Braun 1996). This gas has been variously referred to as the 'Diffuse Ionized Medium' (DIM), 'Diffuse Ionized Gas' (DIG), and 'Warm Ionized Medium' (WIM). In this paper we will adopt the acronym 'DIM'. In the best studied case of the edge-on galaxy NGC 891 (Dettmar 1990, Rand, Kulkarni, & Hester 1990), a DIM in form of filaments and bubbles can be detected out to more than a few kiloparsec from the disk mid-plane (see also Rand 1997). A DIM with similar chaotic structure can be seen in some other face-on late-type galaxies like M 33 and M 31 (e.g. Courtes et al. 1987; Walterbos & Braun 1994). This diffuse gas is (like the Reynolds Layer) characterized by the relative strength of low-ionization emission-lines like [OII]λ3727, [SII]$\lambda\lambda$6717,6731 and [NII]λ6584 (e.g. Dettmar & Schulz 1992; Hunter & Gallagher 1997; Ferguson et al. 1996b).

More generally, Lehnert & Heckman (1994) have shown that the integrated optical spectra of a large sample of normal late type galaxies published by Kennicutt (1992a,b) provide very suggestive evidence that the DIM is generic to such galaxies: the global value of the [SII]/Hα emission-line ratio is enhanced by an average factor of about 1.5 to 2.0 relative to the value characteristic of individual extragalactic HII regions. Based on the emission-line ratios in the DIM in the Milky Way and NGC 891, they estimated that the DIM would generically contribute at least 25% of the total Hα emission in such galaxies. Indeed, direct Hα imaging of several nearby star-forming galaxies has confirmed this estimate. The fraction of the DIM contribution is in the range of $\sim$20%–40%, fairly independent of Hubble type (ranging from early-type spiral(Sb) to irregular) and galaxy inclination (Kennicutt et al. 1995; Ferguson et al. 1996a,b; Hoopes et al. 1996; Hunter & Gallagher 1997).

While the DIM is apparently ubiquitous, its dynamical state and its ionization and heating mechanism(s) are still poorly understood. To improve our understanding of the structure and evolution of the interstellar medium in our own and other galaxies, we need answers to questions such as how the DIM in external galaxies is energized and how much the DIM in the Milky Way shares in common with the extragalactic DIMs. Thus, we need to verify that DIMs are indeed generic in normal star-forming galaxies, and to elucidate the properties of the DIM in such galaxies. We have therefore conducted an investigation of a carefully selected sample of the nearest, largest, and brightest normal late type galaxies. We have selected our sample of galaxies according to the following criteria: 1) Late Hubble type (Sb or later). Such galaxies have relatively strong and easily studied optical line emission (typical global Hα equivalent widths of 30 to 100$\mathring{A}$—cf. Kennicutt 1992a,b). The integrated emission-line spectra of such galaxies contain a substantial contribution from low-ionization gas (Lehnert & Heckman 1994). 2) Nearby (distance < 10 Mpc). This allows us to obtain images with the highest possible spatial resolution ($1''$ is typically 20-50 pc), which is crucial for detecting faint filamentary emission and determining its morphology and structure. 3) Large angular size (D$_{25}$ $\geq$10$'$), so that we have the maximum number of resolution elements across the galaxy. 4) Inclination $\leq$ 65°. We exclude galaxies seen nearly edge-on where line-of-sight projection effects become severe.

In this paper, we report our first results for five galaxies in the sample: M 51, M 81, M 101, NGC 2403 and NGC 4395. Some properties of these galaxies are summarized in Table 1. Our data consist of both narrow-band Hα images and long-slit spectroscopic observations. The spectra provide information on emission lines from Hα, [SII]$\lambda\lambda$6717,6731, and [NII]λ6584 in all five galaxies and on the Hβ, [OIII]λ5007, and [OI]λ6300 lines in subsets of the sample. These data allow us to address the morphology and global energetics of the DIM, as well as its physical and dynamical state. Specifically, we focus on the measurements of the DIM contribution to the global Hα luminosity, the physical state of the DIM (as probed via the relative strengths of the above emission-lines), the dynamical state of the DIM, and the inter-relationship between these physical and dynamical conditions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Hα Imaging Observations

Our imaging data were obtained during February 23-28, 1995, with the 0.9 meter telescope at KPNO. We used a Tek 2048×2048 CCD with a 0.68″ pixel size, yielding a field of view of 23.2×23.2 arcmin^2. The Hα filter had a FWHM of 26$\mathring{A}$ and was centered on 6562$\mathring{A}$. Thus, relatively little flux from the [NII]]$\lambda\lambda$6548,6584 was included in these 'on band' images. 'Off-band' observations of the continuum were made with a narrow band filter having a FWHM of 85$\mathring{A}$ centered on 6658$\mathring{A}$. Several 1800(600) second exposures were taken through the Hα (continuum) filter for each object.

Data reduction was done using the IRAF package following standard procedures. Images were bias-subtracted first and flat-fielded with a master flat combined from a set of many dome flats. Sky-subtracted images were then geometrically rectified to align Hα on-band images with the off-band images.

The limit to the detection of diffuse, low-surface-brightness Hα emission in our data is set by the accuracy with which the contribution of continuum emission in the on-band image can be subtracted (since the DIM Hα emission has a small equivalent width). In this regard, the images are inferior to long-slit spectra with a spectral resolution matched to the intrinsic line-widths of the Hα emission-lines (to maximize the contrast of the lines against the continuum). We have therefore done this continuum subtraction in our images by scaling the off-band image such that difference image agreed with the distribution of the Hα surface brightness in the long-slit spectra (see below) in the region of overlap.

To make this comparison, we first sliced the continuum-subtracted Hα line images in the regions covered by the slit in the relevant spectral observations. We then reproduced the spatial profile of Hα surface brightness variation in the same regions and compared to that shown by the spectra (see §2.2 for details of making the similar profile for Hα line in the spectra). By making small iterative adjustments to the scaling factor for the off-band image, we were able to get good matches of the profiles between the imaging and spectral data. This allowed us to obtain the final, most reliable continuum-subtracted Hα images.

Photometric Hα imaging observations of giant HII regions in these galaxies (Kennicutt 1988) were used to flux-calibrate our images. We have also used our long-slit spectra to check for consistency, and find that the agreement in Hα flux in the regions of overlap is better than 10% for NGC 2403, NGC 4395 and M 101 and 30% for M 51. This suggests our spectra of Hα were taken under nearly photometric conditions (see below).

Internal extinction in the galaxies has not been corrected for. Since the Galactic HI column density in the directions toward these galaxies is low, we did not correct the images for foreground Galactic extinction extinction (it is listed in Table 1).

2.2.   Optical Spectroscopic Observations

Our spectroscopic observations of these five galaxies were made using the RC spectrograph on the 4 meter telescope at Kitt Peak National Observatory during February 17-18, 1996, December 2-3, 1996, December 4-5, 1996, January 31 - February 1, 1997 and February 3-4, 1997. The T2KB CCD was used as the detector, resulting in a scale of $0.69''$ per pixel. A $5'$-long, $2''$-wide slit was placed sampling the nuclei as well as representative spiral arm and inter-arm regions of our sample galaxies. The position angle of the slit for each galaxy is listed in Table 2 and shown in Figure 1. Based on HI velocity maps, the slit orientation was chosen to be near the kinematic minor axes of the each galaxy. This was done so that the velocity gradient of the emission-line gas along the slit should be minimized (allowing us to sum up the emission from large regions along the slit without introducing line-broadening due to large-scale velocity shear). We also insured that the amount of atmospheric differential refraction across the slit was insignificant for the particular slit position angles and hour angles of the observations.

Table 2 lists the spectrograph setup and relevant observation information. One set of data (hereafter the 'red spectra') covers the wavelength range from 6050 to $7090\text{\AA}$ centered at Hα. Because of vignetting in the spectrograph camera and focus variations across the detector, the useful spectral range is limited to the region from 6180 to $6950\text{\AA}$. The data were obtained with the grating KPC-24 in second order. The resolution as determined from FWHMs of night sky lines is about $0.8\text{\AA}$ (37 km/s) FWHM at Hα, allowing determination of deconvolved line widths as small as $\simeq$20 km/s in data with high signal-to-noise (7:1 or better). This can be compared with the minimum Hα FWHM due to pure thermal broadening of 22 km/s for T $= 10^4$ K.

The second set of data (hereafter the 'green spectra') covers the useful wavelength range from about 4400 to $5300\text{\AA}$, and includes the Hβ and [OIII]λ4959,5007 lines. The spectral resolution as determined from FWHMs of strong emission lines in arc lamp spectra ranges from 1.0 to $1.5\text{\AA}$ FWHM (60 to 90 km/s). These data were obtained with either grating KPC-24 or grating KPC-18C in second order. The green spectrum of N 2403 was taken twice on different nights and the data were combined after proper reduction to achieve high S/N ratio.

The data were reduced following standard procedures of biasing and flat-fielding. Wavelength calibration was done with the package TWODSPEC.LONGSLIT in IRAF, using Thorium-Argon or Helium-Neon-Argon arc lamp exposures. The uncertainty in wavelength after calibration for our high resolution spectra was found less than $0.2\text{\AA}$ by comparing wavelengths of night sky lines with standard values.

Since the galaxies have angular sizes that exceed the slit length, night sky spectra were taken immediately before and after object exposures, and were used to subtract the sky. To avoid introducing significant noise, we fit the night sky spectra in the spatial direction with a low order (no higher than 4th) polynomial and used the fits (rather than the actual sky spectra) to do the sky subtraction. The relative strengths of night sky lines varied during the observations in an unpredictable way. Thus, a straightforward method of subtracting a sky frame from a

object frame may not remove some night sky lines completely, especially near the Hα,[NII], and [OI]λ6300 lines in the red spectra. We instead adjusted the scaling factor for sky subtraction interactively in different wavelength ranges until a visually acceptable subtraction was done. As a result, different scaling factors were used as necessary to subtract the sky in the red spectra near the Hα, [NII], [SII], and [OI] lines respectively. In the green spectra, the problem was lessened as there are no strong night sky lines near Hβ and [OIII]λ5007. Only small residuals were left after sky subtraction and they could be treated as additional background noise.

Spectra of the standard stars BD +262606, Feige 34, G191B2B and HZ 44 were taken to do spectrophotometric calibration. For the red spectra, the comparison between the spectra and our flux-calibrated Hα image (see §2.1) suggest that the absolute fluxes of these spectra were very close to photometric values. We extrapolated the green spectra to the spectral region covered by our red spectra and found both set of spectra show consistent flux scales. This indicates that the green data were obtained under photometric conditions as well. Cosmic rays near important emission lines have been removed with IRAF task IMEDIT before measurements.

We have then constructed the spatial profiles of the Hα surface brightness variation along the slit. To do so, the BACKGROUND task in IRAF was employed to fit (in the wavelength direction) the stellar continuum in the spectral region near Hα. To correct for the effect of the broad underlying stellar Hα absorption-line, we used a 4th order polynomial to model the absorption line profile. Because the Hα emission line is almost always very narrow compared to the absorption feature, the emission line could be automatically rejected by the fitting program and therefore only the absorption line profile was fitted. The fits were subtracted from the original data to obtain the pure Hα emission-line fluxes. Although a polynomial is not an accurate representation of the real absorption line profile, this method has been very efficient and successful in removing most of the underlying absorption. The spatial profile of Hα surface brightness was then derived from the absorption-corrected spectrum. The profile was used to locate the regions where the faint gas is, and served as a reference for the continuum subtraction of our imaging data as well (§2.1).

There has been no unique way to isolate the DIM from the rest of a galaxy. Here we simply set an upper limit of 5×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2} to Hα surface brightness for the diffuse gas, corresponding to an emission measure of 25 cm^{-6} pc at an electron temperature of 10^4 K. We used this limit to separate spectra of the diffuse gas from that of HII regions and obtained a set of apertures for spectra of the DIM. The red and green spectra were spatially registered using the positions of a few HII regions along the slit. Thus, the Hα surface brightness criterion can be applied to both sets of spectra, ensuring that the measured line emission of Hβ and [OIII] (green data) in a given aperture is from the same spatial region as the Hα, [NII] and [SII] (red data). The spectra were binned spatially as necessary for adequate detection of DIM emission lines. For very weak lines such as [OI] and [OIII], the spectra had to be summed over many apertures in order to make a measurement. In these cases, we selectively added apertures together and avoided apertures associated with very noisy spectra. This way we could achieve the optimal S/N ratio to detect the weak lines.

The IRAF task SPLOT was used to interactively measure integrated fluxes, centroids, and widths of the emission lines, assuming a single Gaussian for all the emission lines. The measured linewidths were deconvolved using the instrumental resolution to give true widths. Since the instrumental resolution varied slowly as a function of wavelength and position along the slit, we were careful to use the local value of the instrumental resolution for this deconvolution (as determined from night sky lines and the arc lamp exposures).

Since the absorption features of Hα and Hβ are usually very broad (FWHM>20$\overset{\circ}{A}$) and shallow while the emission lines are usually very narrow (FWHM $\leq$2$\overset{\circ}{A}$), it is possible to correct for the absorption in a more rigorous manner than fitting the absorption features with a polynomial as discussed above. In most cases, the narrow Balmer emission lines appear on top of the broad valley of the absorption lines. It suffices to integrate the emission-line flux by simply setting the base of the Balmer emission lines as the continuum level. In rare cases in which the absorption features are only moderately broader than emission lines and further correction needs to be done, we compared the wings of the absorption features with those in typical A-type star spectra (Jacoby, Hunter & Christian 1984). A good match allowed us to estimate how much emission is absorbed underlying the emission lines. Because of the narrow Balmer line widths of the DIM, there is negligible flux missed in the direct measurement of these emission lines with SPLOT.

For measurements of the Hα, [NII]λ6583, and [SII] λ λ6717,6731 emission-line fluxes in the DIM, we summed spatially along the slit such that a S/N ratio of at least 10:1 was achieved in the emission-line fluxes. The Hβ and [OIII]λ5007 lines are relatively faint, so regions along the slit were summed to yield a minimum S/N ratio for these measured fluxes of 5:1.

We also measured the spectra of HII regions in the off-nuclear areas, defined to have Hα surface brightness above 2×10^{-16} erg s^{-1} cm^{-2} arcsec^{-2} (EM above 100 cm^{-6} pc). In this way we have sampled the brightest HII regions in our spectra, which can serve as a contrast to the diffuse gas. The M81 spectra do not cover this type of bright HII regions and were not measured this way. In addition, individual HII regions which appeared to be relatively isolated (not blended with other HII regions) were selected in order to study radial variations of the emission-line ratios [NII]λ6583/Hα and [SII]$\lambda\lambda$6717,6731/Hα from the HII region out into the surrounding DIM. To do so, the spectra were extracted with 2–4$''$ long apertures marching outward from each HII region. The size of the aperture was chosen so that the S/N ratios of measured emission-line fluxes were at least 5:1.

The precise specifications of the spectroscopic apertures used and the resulting measurements of line ratios, line widths, and surface brightnesses for the DIM and HII regions are given in Tables 3 and 4 for the red and green spectra respectively.

3.   RESULTS

3.1. Hα Images

The Hα images of our sample galaxies are shown in Figure 1. The images have been smoothed with a box having a size of $2'' \times 2''$. A faint, diffuse gas component can be seen throughout the disks of these galaxies. The detection of extremely faint gas is affected by the uncertainty of continuum subtraction of the images. But as discussed in §3.2, the wide distribution of the DIM has also been confirmed by our spectra, which have a higher sensitivity. The diffuse gas is preferentially along the edges of spiral arms and around isolated HII regions, as generally the case for the DIM (e.g. Ferguson et al. 1996a; Hoopes et al. 1996). For M 81, the bright diffuse gas component within a radius of 2–3′ from the nucleus seems to not be associated with any prominent star-forming regions and is probably different in nature from the DIM seen elsewhere. The LINER-type nucleus in this galaxy or a population of hot post-main-sequence low-mass stars may play a role in energizing the gas (Devereux, Jacoby, & Ciardullo 1995, 1996).

To study the DIM contribution to the total Hα flux in our sample, we clipped out discrete HII regions at a given surface brightness level from the unsmoothed images and smoothed the images with a $2'' \times 2''$ box. Because the average surface brightness of the DIM ($\sim$10 pc cm^{-6}) is comparable to the noise of the background of the resulting clipped images, we determined the flux from these images by integrating from -3σ of the background of the images to the clipping surface brightness level. We repeated this process over a range in the clipping threshold in surface brightness (emission measure). Figure 2 shows the fraction of total Hα flux the gas contributes as a function of emission measure cut-off. Figure 2 serves only as a rough estimate of the DIM contribution. The measurement was not made below a surface brightness corresponding to 3σ above the background of the unsmoothed images. This minimum clipping surface brightness level corresponds to an emission-measure of 90 pc cm^{-6} for M 51 and M 101, 40 pc cm^{-6} for M 81 and NGC 2403, and 60 pc cm^{-6} for NGC 4395. The depths of the images do not significantly affect the overall result in Figure 2.

There are four effects that should be noted when interpreting Figure 2. First, the light from HII regions, scattered by the optics in the telescope and camera and by the dust in the galaxies, have not been corrected. Hoopes et al. (1996) showed that this correction is minor for their sample galaxies. Furthermore, the emission-line ratios of the DIM (see §3.2) are significantly different from that of typical HII regions. No scattering processes can account for this difference. Thus, scattered light is unlikely dominant in the DIM flux and we do not consider this effect here. Second, a more reliable determination of this contribution should include a correction of the missed diffuse gas flux on top of clipped-out HII regions. A simplified method of making this correction (by assuming the diffuse gas in the clipped-out regions has the mean surface brightness level measured elsewhere (e.g. Ferguson et al. 1996a; Hoopes et al. 1996) may increase the DIM fraction significantly, especially for low cut-off levels. At 50 pc cm^{-6}, the correction factor may be up to 2 (Hoopes et al. 1996). Third, for the purpose of our study, we did not indicate the uncertainty in continuum subtraction in Figure 2. Based on our comparison of our spectra and images, this uncertainty is minor at the relevant levels of emission measure, and will not alter

the essential behavior of the growth curve. Fourth, no extinction correction has been applied. In a situation in which HII regions suffer more average extinction than the DIM, the intrinsic DIM fraction should drop accordingly.

The growth curves shown in Figure 2 vary among our sample galaxies. M 51, M 101 and NGC 2403 have an abundance of very bright HII regions in their disks. In these three galaxies the DIM contributes to the global Hα luminosity at a relatively low level. NGC 4395 and M 81 have a smaller number of bright HII regions and so the DIM becomes more important globally. We verified that the high DIM fraction in M 81 is not due to the prominent diffuse gas component in the inner disk or bulge. To do this test, we masked out a circular region within a radius of 2.5$'$ from the nucleus and constructed the growth curve again. The result showed little difference from that in Figure 2. Thus, the high fraction of the DIM contribution is purely due to the fact that M 81 is a quiescent, early-type spiral.

We have compared the growth curves of the three galaxies in the Sculptor group shown by Hoopes et al. (1996) with ours. NGC 300 has a growth curve very similar to NGC 4395 and M 81 while NGC 253 and NGC 55 match our sample galaxies M 51, M 101 and NGC 2403 well. The variation of the growth curves among galaxies is then not primarily due to inclination. For example, M 101 and NGC 253 have inclination angles of 17° and 78° respectively, yet both galaxies show similar growth curves. The contribution of the DIM to the total Hα luminosity is probably a function of global star formation strength too. Obviously, the galaxies abundant in luminous giant HII regions tend to have a smaller fractional contribution to Hα luminosity from the DIM.

Although we (and others) have defined the DIM in terms of a surface-brightness criterion, the D in DIM stands for 'Diffuse'. Thus, we have also tried to characterize the relative importance of the DIM in each galaxy using a measurement that involves only the structure or morphology of the Hα images. While some rigorous approach based on a Fourier analysis of the images could be attempted, we have just characterized the 'DIMness' of the galaxy by taking the ratio of the mean and the r.m.s. of the Hα surface-brightness within the surface area of the galaxy delimited by the 25 B magnitude per square arcsec isophote. These results (and all the global properties of the Hα images we have measured) are listed in Table 5. Using the ratio of the mean/r.m.s. as a measure of DIMness, we find that M 101 stands out from the rest of the sample. It is dominated by very bright giant HII regions that occupy only a small fraction of the disk surface area, and has a correspondingly small ratio of mean/r.m.s.

Interestingly, M 51 has a pronounced 'diffuse' Hα emission, based on its high value of mean/r.m.s. This morphological criterion thus yields a result that contrasts sharply with the 'growth curve' shown in Figure 2. That is, M 51 has a very small contribution from gas with low surface-brightness (Figure 2), but its emission is relatively diffuse (Table 5). It remains to be seen whether the absolute surface-brightness or the morphology is the more fundamental and physically-meaningful way of defining the DIM.

3.2. Spectroscopic Data

3.2.1. Overview of Properties of the DIM

Because of the better sensitivity of the spectral data compared to the images, the spectra can provide us with detailed information about the global distribution of the very faint DIM. One of the most interesting results from our spectroscopic data is that we can see truly diffuse, low-surface-brightness emission-line gas almost everywhere along the slit.

This is illustrated in Figure 3, which shows the sections of the long-slit spectra containing emission lines of interest, and in Figure 4 which plots the surface brightness distributions of Hα, [NII], Hβ, and [OIII] along the slit for galaxies for which we have data of sufficient quality. Hα+[NII] can be easily seen almost everywhere along the slit except for the [NII] emission in the NGC 4395 spectrum. Thus, we also include in Figure 3 the [SII] emission for NGC 4395 which shows detectable emission everywhere. The relative weakness of the [NII] emission throughout NGC 4395 is most likely an abundance effect (as we will discuss below).

Reliable detections of the [OIII]λ5007 and Hβ lines were made in the DIM in all case except for M 81 (where the stellar background is very bright). The [OI]λ6300 line was reliably detected only in the DIM of NGC 2403 (Figure 3). A noticeable feature in the green spectra of these galaxies is that [OIII]λ5007 for the diffuse gas can sometimes be stronger than Hβ in the same spatial regions (the opposite of the usual case in the HII regions). We will discuss this in detail below.

As can be seen in Figure 4, faint gas can be clearly seen below our arbitrary Hα surface brightness limit for the DIM ($< 5\times10^{-17}$ erg s^{-1} cm^{-2} arcsec^{-2}). We reject the possibility that the diffuse emission is mainly from light of HII regions scattered into the line of sight because this is inconsistent with the pronounced differences in the emission-line ratios between the DIM and the HII regions (as we will show in the following section). Thus, our spectroscopic data shows that the DIM is apparently ubiquitous throughout the inner disks of late type galaxies.

To verify the suggestion made by Lehnert and Heckman (1994) that the DIM significantly contributes to the integrated spectra of normal star-forming galaxies, we measured the [NII]/Hα, [SII]/Hα, and [OIII]/Hβ ratios from the integrated spectra. In these we excluded the nuclear contribution from within the central $\sim$25$''$ aperture because the slit length is only 5$'$ (so our original spectra may be biased towards the nuclear spectra, which may not be representative of the galaxy disk). We then find that for each galaxy the [NII]/Hα and [SII]/Hα ratios from the integrated spectrum are enhanced relative to the corresponding HII region values in the same region of these galaxies by a factor from 1.1 to 2, while the [OIII]/Hβ ratio shows a range of behavior, but no systematic trend (Table 6). This is quantitatively consistent with the results of Lehnert & Heckman (1994) based on the analysis of the Kennicutt(1992a,b) sample.

3.2.2. Line Ratios of DIM

Figure 5 shows representative spectra of the DIM in our sample galaxies near the Hα, [NII], [SII], and [OIII] lines. As can be seen in Tables 3 and 6, and Figure 5, the spectra of the DIM in our sample galaxies have relatively strong low-ionization forbidden lines of [NII]λ6584 and especially [SII]λλ6716,6731 compared to Hα. This is typical of the DIM in our own and other previously-studied galaxies. The contrast between the spectroscopic properties of the DIM and the high-surface-brightness gas in the HII regions in these galaxies can clearly be seen in Figure 6, where we have plotted the ratio of the [SII]/Hα lines versus the ratio of the [NII]/Hα for the DIM and HII regions. These line ratios are typically enhanced by about a factor of three in the DIM compared to the HII regions (see Table 6).

Note that while there is a strong correlation between [NII]/Hα and [SII]/Hα in our sample, the [NII]/Hα ratios in NGC 2403 and NGC 4395 are systematically low compared to the other sample galaxies. This is most likely due to a lower N/S abundance ratio in the two former galaxies. As shown by the Vila-Costas and Edmunds (1993), the origin of nitrogen has both a primary component and a secondary one, implying the nitrogen abundance scales linearly with metallicity at low metallicity but quadratically at medium and high metallicity. This means that the nitrogen abundance is more sensitive to metallicity variations compared to other heavy elements such as sulfur, and that the N/O and N/S ratios decrease with decreasing metallicity. Given the correlation between metallicity and absolute magnitude in late-type galaxies (e.g. Zaritsky, Kennicutt, & Huchra 1994; Skillman, Kennicutt & Hodge 1989), it is natural that NGC 4395 and NGC 2403 would have the lowest metallicities in our sample (see Table 1). In fact, measurements of the O/H and N/O abundances in the bright HII regions in the inner parts of these galaxies (Villa-Costas & Edmunds 1993) support this idea: the N/O ratios ranges from roughly twice solar (M 51), to roughly solar (M 81 and M 101) to about 40% solar (NGC 2403 and NGC 4395).

In our initial analysis we have selected the extremes in surface brightness in the ionized gas (the DIM and the giant HII regions). To further explore the behavior of the [NII] and [SII] lines, we then have measured the relative strengths of these lines as a function of radius from the center of several giant HII regions in each galaxy. These HII regions were selected to be bright and spatially-isolated from other HII regions to allow us to track the transition from giant HII region into the surrounding DIM. The positions of the selected HII regions relative to the nuclei are $100''$ NE and $113''$ SW for M 51, $117''$ SE and $82''$ SE for M 101, $66''$ SW for NGC 2403 and $37''$ NE for NGC 4395. The results are shown in Figure 7, where we can see that there is generally a smooth and monotonic increase in the [SII]/Hα and [NII]/Hα ratio with increasing distance from the core of the HII region. This result emphasizes the *continuity* in properties between the high and low surface-brightness gas.

This continuity can be seen explicitly in Figure 8, which plots the dependence of the [SII]/Hα ratio as a function of Hα surface brightness. This plot contains all the regions that we have measured (the HII regions, the DIM, and the transition regions of intermediate surface-brightness

around the isolated HII regions). The plot shows that the [SII]/Hα ratio is strongly and inversely correlated with surface-brightness over more than two orders-of-magnitude in surface-brightness, and for all five galaxies. The [NII]/Hα ratio exhibits a similar behavior, but the galaxy-to-galaxy scatter is larger, presumably due to the variation in the N/O abundance ratio among the galaxies (as discussed above).

The [OI]λ6300 line—which is a tracer of warm neutral gas, and a unique probe of the DIM—is difficult to detect in our spectra. The [OI] line in M 81 is coincident with the strong Telluric [OI] line, while the [OI] line in NGC 4395 is coincident with another sky line at $\sim$6306.9$\AA$. So no useful measurements in these two galaxies were possible. In the other galaxies we have summed all the DIM data into a single spectrum per galaxy. We then have made marginal (5σ) detections in M 101 and M 51, and a firm detection in NGC 2403. In these three cases the relative intensity of the [OI] line is 0.1 to 0.2 of Hα (Table 6). These ratios are about an order-of-magnitude larger than in the corresponding HII regions ([OI]6300/Hα $\approx$0.01–0.03).

While the enhanced strengths of the low-ionization lines due to [OI], [SII], and [NII] are not surprising in the DIM, our data imply that the relative strength of the high-ionization [OIII]λ5007 line is enhanced in the DIM relative to the giant HII regions in most of our sample galaxies. This can be seen in Table 6 and Figure 9. This result is quite surprising if the DIM is simply photoionized by a dilute radiation field due to the same population of stars that excite the the giant HII regions (the 'leaky HII region model'). In this case, the enhanced low-ionization lines in the DIM would be attributed to a lower ionization parameter U (the ratio of ionizing photons to electrons) in the DIM compared to that in the HII regions (cf. Domgörgen & Mathis 1994). The simplest version of these models would therefore require that the [OIII]/Hβ ratio should drop as we move from the giant HII regions into the DIM. Unfortunately, since the [OIII] surface brightness is too low in our data, we can not directly test this prediction by plotting the radial variation of the [OIII]/Hβ line ratio across individual HII regions (as we do for other lines in Figure 7).

3.2.3.   Kinematics

While there have been many recent studies of emission-line ratios in the DIM, these studies have generally had spectral resolution that was too low to probe the kinematics of the DIM. In contrast, our spectra are able to resolve the emission-line widths throughout the DIM and in most of the giant HII regions. This has led to several surprising and illuminating results.

We begin with a discussion of our results for the Hα and [NII]λ6584 lines, since these are the two brightest lines in the DIM and since our red spectra had better velocity resolution than the green data (instrumental FWHM of typically 40 km/s and 75 km/s respectively). From Figure 10 we see that there is an overall weak trend for the deconvolved (intrinsic) emission-line widths of these two lines to inversely correlate with the Hα surface brightness. Typical Hα and [NII] emission-line widths range from 30 to 100 km/s FWHM in the DIM, compared to typically 20

to 50 km/s in the giant HII regions (recall that pure thermal Doppler broadening at T = 10^4 K produces a FWHM of about 22 km/s for Hydrogen). We conclude that the low-ionization gas in DIM is less quiescent than in the HII regions, but the velocity dispersions are still small compared to theoretical expectations for gas that has been shock-heated and pushed to large scale-heights out of the disk (as we discuss in detail in §4).

Given the strong correlation we find between the [SII]/Hα line ratio and Hα surface-brightness (Figure 8), it is not surprising that there is a trend for the [SII]/Hα ratio to be positively correlated with the Hα and [NII] emission-line widths (Figure 11). The trend is the same for the [NII]/Hα ratio, but with more scatter (again, presumably reflecting galaxy- to-galaxy variations in the N/O abundance ratio). This correlation between the physical state of the gas (line ratios) and the dynamical state of the gas (line widths) suggests that mechanical heating may play some role in exciting the low-ionization lines in the DIM. However, the best correlation of line ratio is with surface-brightness (compare Figures 8 and 11).

We now turn our attention to the [OIII]λ5007 emission-line kinematics. This line is very faint in the DIM and we have had to sum up large regions of DIM to attain a high enough signal-to-noise to make measurements of the line widths (see Table 4). Nevertheless, we find that not only can we spectroscopically resolve the [OIII] line profiles, but that the deconvolved line widths are significantly larger than the Hα and [NII] lines in the same region of the DIM (Figure 5). This can be quantitatively evaluated in Figure 12: typical deconvolved [OIII] line widths are 70 to 150 km/s in the DIM, or about a factor of 1.5 to 2 larger than the [NII] line widths. We emphasize that the line widths plotted in this figure were measured for *exactly* the same spatial region for the [OIII] and [NII] lines. Thus, the greater widths of the former can not be attributed to a systematic velocity gradient over the (by necessity) large extracted region where the measurements were made.

This result has several immediate implications. First, 'The DIM' can not be understood as a single physically and dynamically homogeneous region. Thus, simple single-component models that attempt to reproduce all the emission-line ratios in the DIM will give misleading results. Figure 12 implies that there are at least two components to the DIM. One region (hereafter the 'quiescent DIM') produces most of the Hα, [NII]λ6584, and [SII]λ6717,6731 line emission. A second region (hereafter the 'disturbed DIM') produces most or all of the high-ionization [OIII]λ5007 line emission. The different kinematics of the high-ionization and low-ionization material imply that the two components of the DIM will almost certainly have different spatial distributions in the direction normal to the galactic disk. The high-ionization gas (disturbed DIM) should have a significantly larger vertical scale-height, and therefore be relatively more important in the 'extra-planar' DIM seen in some edge-on disk galaxies. We will quantify this in §4.2 below.

Even if the gas in the quiescent DIM has a very low ionization state, and therefore produces only a negligible amount of [OIII]λ5007 emission, the gas in the disturbed DIM must still produce a non-negligible amount of Hα emission. That is, for any plausible model for the heating of this

gas, the Hα emission in the disturbed DIM will be at least 30% as strong as [OIII]λ5007 (see §4.1 below). We measure the Hα line to be typically about three times brighter than [OIII] line in the DIM (Table 6). Thus, the disturbed component of the DIM ought to contribute at least 10% to the total Hα emission in the DIM. We have therefore reanalyzed our data to see whether the Hα emission-line profile shapes in the DIM can be understood in terms of a strong narrow component (contributed by the quiescent DIM) and a weak broader component (contributed by the disturbed DIM). The modest signal-to-noise in our data allows us only to say that any broad component can contribute no more than about 20% to the total Hα line flux, consistent with an expected minimum value of 10%.

4. DISCUSSION

4.1. The Energy Source for the DIM

4.1.1. Photoionization

The results in §3.2.3 suggest that there may be more than one energy source for the DIM. For the quiescent DIM, the 'leaky HII region' model is appealing on a number of grounds. First, radiation from massive stars is the most abundant ionization source in these star-forming galaxies (by about an order-of-magnitude). Second, there is a morphological correspondence between the DIM and giant HII regions (Hoopes et al. 1996; Ferguson et al. 1996a and §3.1 above). Third, we have emphasized the *continuity* in the physical and dynamical properties of the gas in the quiescent DIM and the HII regions (rather than the existence of any well-defined dichotomy). Fourth, the quiescent state of this component of the DIM argues against mechanical heating as the dominant ionization source. Finally, even simple models of photoionization by dilute stellar radiation can readily match the relative intensities of the low-ionization species in the quiescent DIM (as we now show).

The ionization state of photoionized gas is primarily determined by the ionization parameter (U), defined as the ratio of the density of ionizing photons and electrons in the gas. The low ionization state of the quiescent DIM (and the implied low value for U) is a natural consequence of the 'leaky HII region model'. Averaged over the region interior to R$_{25}$, the mean Hα surface-brightness of the disks of our galaxies (including both the DIM and the HII regions) is about 3×10^{-17} erg cm^{-2} s^{-1} arcsec^{-2}. This corresponds to a disk-averaged flux of ionizing photons of about 10^6 s^{-1} cm^{-2} ster^{-1}. If we assume that a fraction f_{DIM} of these reach the DIM, then we find U $= 2\pi \times 10^6 f_{DIM}/n_e c$ as the characteristic value of U.

We can evaluate n_e by taking a temperature appropriate for photoionized gas (T $\sim 10^4$ K), and assuming the DIM is in pressure-balance with the rest of the ISM. In the solar neighborhood, P/k $\sim 10^4$ cm^{-3} K^{-1}. The surface-mass-density of stars in the inner disks of our galaxies is about an order-of-magnitude higher than the value in the solar neighborhood, while the

surface-mass-density of the interstellar gas is roughly similar to the local value. Provided that the scale-height of this gas is not much less than the scale-height of the stars, simple considerations of hydrostatic equilibrium then imply that the mid-plane pressures in the ISM in the inner disks of our galaxies will be of-order $P/k \sim 10^5$ cm^{-3} K^{-1}. Since these higher pressures are not directly demonstrated observationally, we will use $P/k \sim 10^4$ to 10^5 cm^{-3} K^{-1}. We then obtain U $= 4 \times 10^{-4} f_{DIM}$ to $4 \times 10^{-5} f_{DIM}$ as the characteristic value in the mid-plane. These mid-plane values are appropriate for the quiescent DIM since (as we will show in §4.2 below) it must have a relatively small scale-height.

Note that the actual value of U in the DIM will be larger than the above, since the DIM is spatially-correlated with HII regions and therefore probably sees a photoionizing flux that is higher than the disk-average. On the other hand, f_{DIM} is of-order 10^{-1}. The implied range in U is then consistent with photoionization models that show that the key diagnostic line ratios [NII]/Hα and [SII]/Hα peak for values of U in the range 3×10^{-5} to 3×10^{-4} (e.g. Sokolowski 1993).

This analysis also reveals why the leaky HII region model would have difficulties explaining the *disturbed* DIM. The lack of obvious broad wings on the Hα or [NII] emission-lines (§3.2) implies that the disturbed DIM must have a relatively high ionization state. Photoionization models show that very strong [OIII]λ5007 emission (e.g. [OIII]/H$\beta \gg 1$) requires logU > -2. Using the same arguments as in the above paragraph, values this large for U would require $n_e < 0.02 f_{DIM}$, or $P/k < 4 \times 10^2 f_{DIM}$ cm^{-3} K^{-1}. This pressure is far below plausible ISM pressures. While the hydrostatic equilibrium condition implies that the gas pressure will drop with distance out of the disk plane, the required pressures are so low that the disturbed DIM would have to be located more than 6 pressure-scale-heights above the inner disk (inconsistent with our estimates in §4.2 below).

Perhaps the biggest challenge for photoionization models is explaining the pervasiveness of the DIM. Our new long-slit data showing Hα, [NII], and [SII] emission throughout the inner disk only exacerbates this problem. Here we would like to emphasize the curious fact that the opacity of the ISM to ionizing radiation in these galaxies seems to be 'fine-tuned'. That is, we can imagine two extremes for the fate of ionizing radiation produced by massive stars. First, it may all be absorbed locally around the complexes of O stars so that a deep Hα image would reveal small intense 'islands' of high-surface-brightness surrounded by very dark 'oceans' that cover most of the disk. This is manifestly not the case (cf. Figures 1 and 2). The other extreme case is one in which the ISM is optically-thin to ionizing radiation, allowing it to freely escape into the galactic halo or intergalactic space. This also seems far from reality (Leitherer et al. 1995, Giallongo et al. 1997). Instead, the ISM seems to be arranged such that is optically thin enough to allow the gas throughout a significant fraction of the ISM to be bathed in the diffuse radiation of the hot stars, yet optically-thick enough to capture the great majority of the ionizing radiation. Why is this so? Is this the result of some subtle feedback loop between star-formation and the structure and physical state of the ISM?

4.1.2. Mechanical Heating

While we can not totally rule out photoionization for the disturbed DIM, we are lead to consider a totally different ionization source. The disturbed kinematics of this gas could implicate mechanical heating of the ISM by supernovae and stellar winds. We therefore consider two alternative forms for such mechanical heating: radiative shocks and turbulent mixing layers.

Models of low-density radiative shocks (Shull & McKee 1979; Raymond 1997) show that suitably strong [OIII]λ5007 emission (e.g. [OIII]/Hα = 1 to 3) is attained for shock speeds > 100 km s^{-1}. A strong shock will accelerate the shocked material to 3/4 of the shock velocity, so we would expect the velocity dispersion in the DIM to be > 75 km s^{-1}. The typical measured line widths for the [OIII]λ5007 line imply a 3-dimensional velocity dispersion for the disturbed DIM of 60 to 100 km s^{-1}, so the required shock speeds are plausible.

Turbulent mixing layers (Slavin, Shull, & Begelman 1993) are the interface between hot gas flowing past cold clouds, and hence have a temperature that is intermediate between the cloud and hot phases. The models yield values of [OIII]λ5007/Hα of 1.5 to 3 for much of the parameter space these authors explored. This specific range encompasses mixing layers with logT = 5.3 and 5.5 when the 'cold' clouds have logT = 4, and mixing layers with logT = 5.5 when the cold clouds have logT = 2. Cooler mixing layers do not produce significant [OIII] emission. The turbulent mixing layer models have one advantage over the shock models in that they do not demand that the mixing layer necessarily have a large velocity dispersion. Satisfactorily strong [OIII] emission relative to Hα can be produced when the hot gas moves past the cold cloud at either 25 km s^{-1} or 100 km s^{-1} (consistent with the observed [OIII] line widths in the DIM). High relative velocities do lead to enhanced emissivity at a given gas pressure however (see below).

A potential problem with both the shock and turbulent mixing layers models (especially the latter) is the low predicted [OIII]λ5007 surface brightness for gas having the modest pressures appropriate to a normal disk galaxy ISM (P/k $\sim$ 10^4 K cm^{-3} to $\sim$ 10^5 K cm^{-3} in the inner disk regions probed by our spectra). For P/k = 10^5 K cm^{-3}, the predicted [OIII]λ5007 surface brightnesses from shocks with v = 100 to 150 km s^{-1} are in the range 3×10^{-18} to 7×10^{-18} erg cm^{-2} s^{-1} arcsec^{-2}. This is similar to typical [OIII]λ5007 surface-brightnesses in the DIM of about 5×10^{-18} to 1×10^{-17} erg cm^{-2} s^{-1} arcsec^{-2}. This agreement would then require the areal covering-factor of shocked gas within our slit to be unity. However, the *volume filling-factor* of shocked gas in the galaxy ISM would be much smaller. The shock models of Shull & McKee (1979) scaled to P/k = 10^5 K cm^{-3} imply that the total thickness of the layer of [OIII]-emitting gas would be of-order 0.1 pc per line-of-sight through the DIM (much less than the thickness of the disk ISM).

The surface-brightness agreement is not so good with the models for turbulent mixing layers. These predict [OIII]λ5007 surface brightnesses of 10^{-18} erg cm^{-2} s^{-1} arcsec^{-2} at best, even for P/k = 10^5 K cm^{-3}. This is an order-of-magnitude smaller than the typical observed values in the DIM, and would require the presence of many (> 10) turbulent mixing layers along a typical

line-of-sight through the galaxy disk.

As noted in §1, energizing the entire DIM seems problematic using only the mechanical energy from supernovae and stellar winds, since it requires tapping essentially *all* of this mechanical energy. However,the energetic requirements for ionizing the disturbed DIM alone are substantially less. That is, the disturbed DIM contributes less than 20% to the total Hα luminosity of the DIM (§3.2.2), at least in the regions probed by our spectra. Thus, mechanical heating can not be ruled out on simple energetic grounds.

We have seen that the DIM is very pervasive in the inner disks of our galaxies, so mechanical heating of the DIM would require that nearly every line-of-sight through the disk intersect regions of mechanically-heated gas. It is not clear whether the topology or 'porosity' (McKee & Ostriker 1977) of the ISM in typical disk galaxies is consistent with this requirement. Observationally, there is no direct evidence for a high covering fraction of diffuse gas mechanically heated to a temperature of 10^5 K or more in typical galactic disks. For example, Heiles (1990) and Oey & Clarke (1997) have concluded that only a small fraction of the surface area of the disks of the Milky Way, M 31, and M 33 is covered by the hot superbubbles created by supernovae and stellar winds. On the other hand, the available information about soft X-ray emission from the nearby spiral galaxies suggests the existence of diffuse, relatively hot gas ($T \geq 10^6$ K), but little is known about the corresponding areal covering factor. Perhaps the best studied case of diffuse, soft X-ray emitting gas in our sample galaxies is M 101. Snowden & Pietsch (1995) have shown that in the inner disk of M 101, the gas has $T \simeq 10^{5.8}$ K and a covering fraction of-order unity. To heat up the gas to this temperature requires shock speeds (~ 200 km s^{-1}) that are much larger than the typical line widths that we have observed in the DIM. Certainly, the hot gas seen in the X-ray data may cool and fall back into the disk thereby contributing to the DIM.

4.2.   The Dynamics and Inferred Vertical Extent of the DIM

The observed Hα and [NII]λ6584 line widths in the DIM range from about 30 to 100 km s^{-1} (FWHM), rather similar to the line widths in the Reynolds Layer in our own Galactic disk of ~ 30 to 60 km s^{-1} (Reynolds 1985). Since we have verified that there are no significant velocity shears along the slit in the regions where we have made these line-widths measurements, the broadening must be due to small-scale 'turbulent' motions of the gas. The lines are certainly broader than pure thermal broadening (which is only 22 km s^{-1} FWHM for HI at $T = 10^4$ K). Of course, the [OIII]λ5007 line-widths are larger still: typically 70 to 150 km s^{-1} FWHM.

We can use these line-widths to estimate the corresponding scale-height of the emitting gas, assuming that the gas clouds have an isotropic velocity dispersion and move in a gravitational potential in which they act as test particles. Using optical surface photometry of the disks of our sample galaxies, and taking mass-to-light ratio $M_{tot}/L = 5$ solar units for both V and B bands (e.g. Binney & Tremaine 1987) we estimate that the typical surface mass-density in the inner disks

ranges from 100 to 400 $M_\odot$ pc^{-2}. We further assume that the mass that sets the potential has the form $\rho(z) \, \alpha \, \exp[-z/H]$ where z is the distance out of the mid-plane and H is the scale-height for the mass ρ. In the disk of the Milky Way, H $\sim$ 350 pc (Freeman 1987). Adopting this value, we have then solved for the scale height h_{gas} for an ensemble of gas clouds moving in this potential with a velocity dispersion in the z-direction $\sigma_z = 0.43\times$ (FWHM). The results are listed in Table 7.

From this we see that typical scale-heights for the quiescent DIM (based on Hα and [NII]$\lambda6584$ line widths) are 300 to 500 pc, which is significantly less than the values of 600 to 900 pc for the Reynolds Layer (Reynolds 1993). This is due in part to the much larger surface mass-densities in the inner regions of our galaxies and the associated deeper potential well. The estimated scale-heights for the dominant (quiescent) component of the DIM are in fact typically comparable to our assumed scale-height for the stellar disk (350 pc). Thus, we conclude that *the DIM in the inner regions of our galaxies is not in any sense an 'extraplanar' phenomenon.* This is interesting, since the terms 'DIM' (or 'DIG' or 'WIM'!) and 'extraplanar gas' were often used synonymously in early investigations. In fact, the quiescent state we find for the dominant component of the DIM may naturally explain why the DIM seems to be ubiquitous in late-type galaxies, but striking examples of extraplanar gas are proving to be rare (e.g. Rand 1996a, Rand 1996b).

In Table 7 we also list the derived scale-heights for the disturbed DIM using our measured [OIII]$\lambda5007$ line widths. These scale-heights are typically 400 to 800 pc, or a factor of about 1.5 to 2 greater than for the quiescent DIM. Thus the disturbed DIM might more properly be considered 'extraplanar'. In this regard it is intriguing that Rand (1997) found morphological evidence for two components in the DIM in NGC 891. Since this galaxy is viewed almost exactly edge-on, Rand fit the vertical dependence of the mean Hα surface-brightness in terms of the sum of two exponentials. There is a bright component that provides about 84% of the total emission and has a scale-height of 500 pc, and a faint component that provides the other 16% of the emission and has a scale height 5 to 6 times larger. The bright and faint components must have different kinematics to have such different vertical distributions, and we suggest that they may correspond respectively to the quiescent and disturbed components of the DIM that we have identified kinematically. It would be important in this regard to measure the dependence of the [OIII]$\lambda5007$/Hβ ratio on distance out of the mid-plane in NGC 891 to see in the more extended DIM component has a relatively high ionization state (as we find for the disturbed DIM). The only published [OIII] measurement (Dettmar 1992) is an upper limit at a distance of only 0.5 kpc out of the disk (in the region dominated by Rand's inner DIM component, which we would predict to be of low ionization).

5.   Summary

We have reported on the initial results from a program to study the morphology, physical state, and kinematics of the 'Diffuse Ionized Medium' ('DIM') in a sample of the nearest and brightest late-type galaxies. For each of five galaxies (NGC 2403, M 81, NGC 4395, M 51, and M

101) we have analyzed deep narrow-band Hα images covering essentially the entire star-forming disk (a field diameter of 23.2 arcmin, or 18 to 53 kpc). These images reach limiting Hα surface-brightnesses of about 8–18 $\times 10^{-17}$ erg cm^{-2} s^{-1} arcsec^{-2} (corresponding to an emission measure of about 40–90 cm^{-6} pc). We have also analyzed long-slit spectra covering a single region in the inner disk (5 arcmin, or 4–12 kpc in extent centered on the galactic nucleus). These spectra cover the Hβ and [OIII]λ5007 emission-lines at a velocity resolution of about 75 km s^{-1} (FWHM) and the [OI]λ6300, Hα, [NII]λ6584, and [SII]$\lambda\lambda$6717,6731 emission-lines at a velocity resolution of about 40 km s^{-1}. By summing the spectra over large spatial regions, we have been able to measure emission-lines down to a limiting surface-brightness (5 σ) of about 5×10^{-18} erg cm^{-2} s^{-1} arcsec^{-2} (an emission-measure of 2.5 cm^{-6} pc for Hα).

As in the case of other similar galaxies (e.g. Ferguson et al. 1996a, Hoopes et al. 1996) we find that diffuse low-surface-brightness gas (a 'DIM') covers most of the star-forming disk, and is morphologically related to the presence of high-surface-brightness gas (the giant HII regions). Plots of the cumulative contribution of gas of progressively higher surface-brightness to the integrated Hα flux are very similar to the plots for galaxies in the Sculptor group (Hoopes et al. 1996). We note that the D in DIM stands for 'Diffuse', and utilize the ratio of the mean/r.m.s. Hα surface-brightness to quantify this. M 51 is an example of a galaxy with a pronounced DIM as defined by morphology, but a weak DIM as defined by absolute surface-brightness (it has lots of diffuse, high-surface-brightness emission). *It is not yet clear whether surface-brightness or morphology is the more physically-meaningful way to specify the DIM.*

We find that the DIM and the regions of high Hα surface-brightness (giant HII regions) differ systematically in their physical and dynamical state. The DIM is characterized by enhanced emission (relative to Hα) in the low-ionization forbidden lines ([OI], [NII], and [SII]). This agrees with results for the DIM in other galaxies including our own (cf. Dettmar 1992 and references therein). However, we also find that the high-ionization [OIII]λ5007 line is moderately strong ([OIII]λ5007/H$\beta \sim 1$) in the DIM. This contrasts with upper limits on the [OIII] surface brightness in our own Galaxy and the prototypical edge-on spiral NGC 891 (Reynolds 1990, Dettmar 1992). We directly verify the inference made by Lehnert & Heckman (1994) that the DIM contributes significantly to the spatially-integrated (global) emission-line spectra of late-type galaxies as published by Kennicutt (1992a,b).

We also find that the DIM is more disturbed kinematically than the gas in the giant HII regions. The deconvolved (intrinsic) widths of the Hα and [NII]λ6584 lines range from 30 to 100 km s^{-1} (FWHM) in the DIM compared to 20 to 50 km s^{-1} in the giant HII regions. These can be compared to a width of 22 km s^{-1} for pure thermal broadening of Hα at T = 10^4 K. The high-ionization gas in the DIM is more kinematically disturbed than the low-ionization gas: in the same regions in the DIM we measure the [OIII]λ5007 lines to have typical intrinsic widths of 70 to 150 km s^{-1}.

The differing DIM kinematics seen in the [OIII] and [NII] lines along the same line-of-sight

implies that *the DIM is not a single monolithic phase of the ISM*. Instead we propose that there is a 'quiescent DIM' that is responsible for the majority ($> 80\%$) of the emission in lines like Hα, Hβ, [NII]λ6584, and [SII]$\lambda\lambda$6717,6731, and a 'disturbed DIM' that is responsible for the bulk of the [OIII]λ5007 emission. Considerations of hydrostatic equilibrium in the vertical potential well of the inner disk then imply that the quiescent DIM has a modest scale-height of several hundred pc (probably similar to the scale-height of the old stars). Thus, *the terms 'DIM' and 'extraplanar gas' are by no means synonymous.* The estimated scale-heights for the disturbed DIM are about a factor of two larger (0.3 to 1 kpc). This material would have a higher characteristic ionization state than the quiescent (thin-disk) DIM.

We find that the standard 'leaky HII region model' in which the DIM is photoionized by the diffuse Lyman continuum radiation field from O stars (cf. Domgörgen & Mathis 1994; Sokolowski 1993) can naturally account for the measured properties of the quiescent DIM. The ubiquity of faint Hα emission (which our spectra show to fill essentially the entire inner disk) then leads to an apparent need for some fine-tuning of the physical state of the ISM: *the disk must be optically-thick enough to capture most of the ionizing photons, yet optically-thin enough to allow these photons to permeate the disk.* Why is this so? Is there some feedback loop involving massive stars and the ISM?

In contrast, mechanical heating (which is ultimately driven by the energy supplied by supernovae and stellar winds) is the most natural ionization source for the disturbed DIM. Either radiative shocks (with a shock speed > 100 km s^{-1}) or turbulent mixing layers (Slavin, Shull, & Begelman 1993) can produce relatively strong [OIII]λ5007 emission. Since the disturbed DIM accounts for only a minority ($< 20\%$) of the Hα emission in the regions we have studied, there is no fundamental energetics problem in either case. However, the observed surface brightness of the disturbed DIM requires that essentially every line-of-sight through the inner disk must encounter at least one shock or ten turbulent mixing layers. Direct observational evidence for such a large areal covering factor of mechanically-heated gas in typical galaxy disks is mixed (Heiles 1990 and Oey & Clarke 1997; but see Snowden & Pietsch 1995).

We also have stressed that *there is no clear discontinuity in physical and dynamical properties of the giant HII regions and the quiescent DIM.* The quiescent DIM is morphologically related to the giant HII regions and there is a smooth dependence of the emission-line ratios and emission-line widths on the surface brightness of the emission. In other words, as one moves outward from the HII regions into the DIM, the properties of the ionized gas change in a continuous, regular way. The present data on the disturbed DIM are too limited to make firm statements in this regard, but we are currently investigating this in a much more extensive new data set. In any case, we suggest that a unified view of the warm ionized gas in the disks of star-forming galaxies is likely to be productive.

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Fig. 1.— Continuum-subtracted Hα emission-line images in grayscale. North is to the top and East is to the left. The slit position we used for each galaxy is shown. The scale of the images is represented by the length of the slit of 5′ . *a*) M 51, *b*) M 81, *c*) M 101, *d*) NGC 2403, and *e*) NGC 4395.

Fig. 2.— The growth curve of fractional Hα flux as a function of emission measure cutoff for our five galaxies. Symbols are: stars—M 101, triangles—M 51, solid circles—M 81, crosses—NGC 4395, open circle—NGC 2403. See the text for details about the construction of the curves.

Fig. 3.— Grayscale representation of the DIM 2D spectra. The *y*-axis is the wavelength coordinate increasing from top to bottom. The *x*-axis is along the slit. From left to right, the axis points towards NW for M 101 and towards SW for the rest galaxies. The length of each window is about 5′. a) The strong emission lines [NII]λ6548, Hα and [NII]λ6584. The [SII]$\lambda\lambda$6717,6731 lines for NGC 4395 are included to compliment the weak [NII] lines. b) The weaker lines Hβ, [OIII]λ5007 and [OI]λ6300. The data for those galaxies that have poor S/N in these emission-lines are not shown.

Fig. 4.— a) Spatial profiles of the Hα (solid line) and [NII]λ6584 (dotted line) surface brightness along the slit. One unit along the *y*-axis corresponds to 1×10^{-16} erg s^{-1} cm $^{-2}$ arcsec^{-2}. The coordinate of the *x*-axis increases from SE to NW for M 101 and from NE to SW for the other galaxies. The origin of the *x*-axis is set at the nuclear position. The length of the *x*-axis is about 5′. The upper dashed line indicates the cutoff Hα surface brightness of 5×10^{-17} erg s^{-1} cm $^{-2}$ arcsec^{-2} that we used to isolate the DIM, and the lower dashed line is the zero level. b) Same as a) but for the spatial profile of the [OIII]λ5007 surface brightness (thick solid line). The Hα profiles shown in Figure 4a are arbitrarily scaled and represented by thin solid line for comparison. The data for those galaxies that have poor S/N near [OIII] are not shown.

Fig. 5.— a) Representative DIM spectra near Hα,[NII]λ6583, and [SII]$\lambda\lambda$6717,6731. b) Representative [OIII]λ5007 line profiles compared with [NII]6583 linewidths (illustrated as horizontal bars) that have been convolved to have the same instrumental resolution as the [OIII] data. The [NII]6583 lines were measured from the same spatial regions where we measured the [OIII] lines.

Fig. 6.— *Left panel*: The [SII]$\lambda\lambda$6717,6731/Hα line ratio vs. the [NII]λ6584/Hα line ratio. Data are from the DIM, bright HII regions, and intermediate regions around isolated HII regions as shown in Figure 7. The DIM points lie to the upper right, the HII regions to the lower left, and the intermediate points lie in between (see *right panel*). Data points are grouped for each galaxy and do not distinguish between the DIM and bright HII regions. Symbols are: stars—M 101, triangles—M 51, solid circles—M 81, crosses—NGC 4395, open circles—NGC 2403. The M 81 spectrum does not cover any bright HII regions so we only include measurements for the faint HII regions. *Right panel*: Same as *left panel* except that the data points are grouped by Hα surface brightness(SB). Open square—SB below 5×10^{-17} erg s^{-1} cm $^{-2}$ arcsec^{-2}, which is the cutoff surface brightness we adopted to isolate the DIM, solid square—SB above 2×10^{-16} erg s^{-1} cm $^{-2}$ arcsec^{-2}, which is the lower limit we used to select bright HII regions, square with cross in center—SB below 2×10^{-16} erg s^{-1} cm $^{-2}$ arcsec^{-2} but above 5×10^{-17} erg s^{-1} cm $^{-2}$ arcsec^{-2}.

Fig. 7.— Radial variation of the [SII]$\lambda\lambda$6717,6731/Hα and [NII]λ6584/Hα line ratios across individual HII regions. M 81 is not included due to its lack of bright HII regions. The line ratios are shown to increase smoothly from typical HII region values to DIM values as the curves move from the centers of HII regions to faint, surrounding gas. Solid line—M 101; Dotted line—M 51; Dashed line—NGC 2403; Dot-dashed line—NGC 4395.

Fig. 8.— The [SII]$\lambda\lambda$6717,6731/Hα line ratio vs. Hα surface brightness. Data are from the DIM, bright HII regions, and intermediate regions around isolated HII regions as shown in Figure 7. Data points are grouped for each galaxy and do not distinguish between the DIM and bright HII regions. Symbols used are the same as Fig. 6: stars—M 101, triangles—M 51, solid circles—M 81, crosses—NGC 4395, open circles—NGC 2403. The DIM points lie to the upper left, the HII regions to the lower right, and the intermediate points lie in between. The M 81 spectrum does not cover any bright HII regions so we only include measurements for the faint HII regions.

Fig. 9.— Line ratio diagrams. Solid squares—bright HII region data from M 51, M 101, NGC 2403 and NGC 4395; The DIM data points are represented in the same convention adopted in the previous figures: stars—M 101, triangles—M 51, large crosses—NGC 4395, open circles—NGC 2403. Arrows mean that [OIII]λ5007 is below our 5σ detection limit. Sokolowski(1993)'s standard photoionization model (solid curve) and dust depletion model (dotted curve) are also shown. Small crosses on the curves indicate the value of the ionization parameter U (from lower-right to upper-left along each curve): 3×10^{-4}, 5×10^{-4}, 7×10^{-4}, 9×10^{-4}, 2×10^{-3}, 4×10^{-3}, 6×10^{-3}. The high [OIII]/Hβ point for NGC 4395 is for gas near the Seyfert nucleus.

Fig. 10.— Hα surface brightness vs. deconvolved line width. The line widths are measured from the Hα line if the EQW(Hα) is larger than $3\mathring{A}$ and from [NII]λ6584 if the EQW(Hα) is less than $3\mathring{A}$ (to avoid the effect of stellar Hα absorption). The dashed line marks the lower limit (20 km s^{-1}) below which line widths can not be determined reliably. Data are for the DIM, bright HII regions, and intermediate regions around isolated HII regions as shown in Figure 7. The data point notation is the same as in the previous figures: stars—M 101, triangles—M 51, solid circles—M 81, crosses—NGC 4395, open circles—NGC 2403. The DIM points lie to the lower right, the HII regions to the upper left, and the intermediate points lie in between. The M 81 spectrum does not cover any bright HII regions so we only include measurements for the faint HII regions.

Fig. 11.— The [SII]$\lambda\lambda$6717,6731/Hα line ratio vs. deconvolved line width. The line widths are measured from Hα line if the EQW(Hα) is larger than $3\mathring{A}$ and from [NII]λ6584 if the EQW(Hα) is less than $3\mathring{A}$. The dashed line marks the lower limit (20 km s^{-1}) below which line widths can not be determined reliably. Data are for the DIM, bright HII regions, and intermediate regions around isolated HII regions as shown in Figure 7. The data point notation is the same as in the previous figures: stars—M 101, triangles—M 51, solid circles—M 81, crosses—NGC 4395, open circles—NGC 2403. The DIM points lie to the upper right, the HII regions to the lower left, and the intermediate points lie in between. The M 81 spectrum does not cover any bright HII regions so we only include measurements for the faint HII regions.

Fig. 12.— The deconvolved FWHM of the [OIII]λ5007 line vs. the deconvolved FWHM of the [NII]λ6584 line for regions in the DIM. The solid line is the locus where FWHM([NII]λ6584) = FWHM(OIII]λ5007). The data point notation is the same as in the previous figure: stars—M 101, triangles—M 51, crosses—NGC 4395, open circles—NGC 2403. The arrows imply the [OIII] linewidth can not be determined reliably based on our estimated minimum resolvable linewidth of 40 km s^{-1} for the [OIII] line.

Table 1.   Galaxy Parameters

Object	Hubble Type[a]	i[b]	D(Mpc)[c]	v[d]	$A_{H\alpha}$[e]	$M_{B,T}$[f]
M 51	SbcI-II	64°	8.4	464	0.06	-21.0
M 81	SbI-II	60°	3.6	-36	0.19	-20.8
M 101	ScdI	17°	7.4	251	0.06	-21.5
NGC 2403	ScIII	62°	3.2	131	0.21	-19.2
NGC 4395	SdIII-IV	38°	2.6	317	0.06	-16.7

[a] From Revised Shapley-Ames Catalog(Sandage & Tammann 1987).

[b] Inclination data are from Tully(1988) except the inclination for M 101 is from Zaritsky et al. (1990).

[c] Distances are from Feldmeier et al. (1997) (M 51), Freedman et al. (1994) (M 81), Kelson et al. (1996) (M 101), Karachentsev & Makarov (1996) (NGC 2403) and Rowan-Robinson (1985) (NGC 4395).

[d] Weighted mean observed heliocentric radial velocity from Revised Shapley-Ames Catalog(Sandage & Tammann 1987).

[e] Galactic extinction in magnitude at Hα, estimated based on foreground Galactic HI column density(Stark et al. 1992) in the direction of the objects. The conversion is done by assuming $N_{HI}/E_{B-V} = 5 \times 10^{21}$ cm^{-2} mag^{-1} and $A_{H\alpha} = 2.1$ E_{B-V}.

[f] Total absolute magnitude in B band from Revised Shapley-Ames Catalog(Sandage & Tammann 1987), adjusted to our adopted distance.

Table 2.   Spectroscopic Observations[a]

Object	λ_c (Å)	Coverage[b] (Å)	Grating[c]	Resolution (Å)	PA (°)	Blocking Filter	Standard Star	Date
M 51	6563	6180-6950	KPC-24	0.8-1.0	60	GG495	BD +262606	02/17/96
	4850	4450-5250	KPC-24	1.2-1.5	60	BG39	Feige 34	12/04/96
M 81	6563	6180-6950	KPC-24	0.8-1.0	60	GG495	BD +262606	02/17/96
	4800	4360-5230	KPC-18C	1.2-1.5	60	GG385+CUSO4	Feige 34	12/02/96
M 101	6563	6180-6950	KPC-24	0.8-1.0	140	GG495	BD +262606	02/17/96
	4900	4500-5300	KPC-24	1.0-1.2	140	4-96	HZ 44	01/31/97
NGC 2403	6563	6180-6950	KPC-24	0.8-1.0	35	GG495	BD +262606	02/17/96
	4800	4360-5230	KPC-18C	1.2-1.5	35	GG385+CUSO4	Feige 34	12/02/96
	4900	4500-5300	KPC-24	1.0-1.2	35	4-96	G191B2B	02/03/97
NGC 4395	6563	6180-6950	KPC-24	0.8-1.0	60	GG495	BD +262606	02/17/96
	4800	4360-5230	KPC-18C	1.2-1.5	60	GG385+CUSO4	Feige 34	12/02/96

[a]All observations were made with the KPNO 4m telescope using the RC spectrograph and the T2KB CCD. A slit of 5′ long and 2″ wide is used centered on the nucleus of each of the objects.

[b]Useful spectral range estimated from 1500 pixels of the CCD.

[c]All gratings are set in second order.

Table 3.   Emission-line Properties of DIM Part I. Hα, [NII] and [SII]

Object	Aperture	$\Sigma_{\text{H}\alpha}$ (erg s^{-1} cm^{-2} arcsec^{-2})	$\Delta V_{\text{H}\alpha/\text{[NII]}}$ (km s^{-1})	[NII]/Hα	[SII]/Hα
M 51	92.5-90.5″ NE	3.2×10^{-17}	91	1.7	1.1
	84.9-80.8″ NE	3.5×10^{-17}	89	1.4	0.97
	63.5-52.6″ NE	3.3×10^{-17}	120	1.2	0.66
	46.9-62.0″ SW	2.2×10^{-17}	77	1.4	0.79
	95.2-102.0″ SW	3.8×10^{-17}	78	1.1	0.76
	105.5-107.5″ SW	4.4×10^{-17}	86	0.84	0.37
	117.3-152.4″ SW	1.3×10^{-17}	83	1.5	0.87
M 81	144.9-125.6″ NE	1.3×10^{-17}	97	1.1	1.1
	125.5-119.4″ NE	2.2×10^{-17}	137	1.4	1.4
	119.3-93.9″ NE	8.7×10^{-18}	63	1.3	1.6
	93.8-51.1″ NE	1.8×10^{-17}	120	2.1	1.3
	51.0-47.0″ NE	6.3×10^{-17}	146	2.0	1.5
	46.9-40.1″ NE	4.3×10^{-17}	170	2.6	1.6
	36.5-29.0″ NE	6.0×10^{-17}	108	1.9	1.5
	20.8-28.9″ SW	4.9×10^{-17}	120	2.0	1.3
	29.0-48.3″ SW	2.4×10^{-17}	114	2.1	1.8
	49.0-69.0″ SW	1.6×10^{-17}	79	1.6	1.4
	69.1-100.7″ SW	1.5×10^{-17}	64	1.1	1.1
	105.6-126.2″ SW	1.6×10^{-17}	77	1.0	1.2
	131.8-141.4″ +144.3-151.8″ SW	1.4×10^{-17}	56	0.69	0.83
M 101	144.8-140.0″ SE	4.0×10^{-17}	48	0.57	0.57
	135.8-120.0″ SE	3.6×10^{-17}	35	0.51	0.73
	111.7-86.9″ SE	2.4×10^{-17}	43	0.61	0.72
	77.2-66.2″ SE	3.1×10^{-17}	40	0.74	0.66
	64.1-60.7″ SE	5.1×10^{-17}	45	0.49	0.47
	53.7-46.2″ SE	4.2×10^{-17}	44	0.69	0.54
	42.7-40.7″ SE	4.6×10^{-17}	27	0.61	0.39
	29.6-20.7″ SE	3.7×10^{-17}	79	1.2	0.79
	8.4-15.2″ NW	2.9×10^{-17}	77	2.3	1.3
	15.3-20.7″ NW	1.9×10^{-17}	89	2.7	1.2
	22.2-28.3″ NW	3.5×10^{-17}	83	0.94	0.34
	35.3-45.6″ NW	4.0×10^{-17}	36	0.55	0.36
	49.1-56.6″ NW	4.2×10^{-17}	34	0.55	0.48
	80.2-84.2″ NW	4.3×10^{-17}	47	0.45	0.45
	86.4-117.3″ NW	1.3×10^{-17}	45	1.1	1.1
	117.4-144.2″ NW	2.1×10^{-17}	40	0.64	0.69
NGC 2403	145.1-130.0″ NE	3.4×10^{-17}	51	0.27	0.75
	130.0-119.7″ NE	4.1×10^{-17}	54	0.21	0.67
	74.8-67.3″ NE	5.5×10^{-17}	56	0.30	0.62
	67.2-59.7″ NE	4.4×10^{-17}	54	0.37	0.71
	87.4-103.2″ SW	2.4×10^{-17}	60	0.36	1.1
	103.3-151.5″ SW	1.7×10^{-17}	59	0.37	0.93

Table 3—Continued

Object	Aperture	$\Sigma_{\text{H}\alpha}$ (erg s^{-1} cm^{-2} arcsec^{-2})	$\Delta V_{\text{H}\alpha/[\text{NII}]}$ (km s^{-1})	[NII]/Hα	[SII]/Hα
NGC 4395	146.0-90.9″ NE	9.3×10^{-18}	42	$\cdots$	$\cdots$
	90.8-79.2 ″ NE	3.1×10^{-17}	29	$\cdots$	$\cdots$
	79.1-39.2″ NE	1.6×10^{-17}	47	$\cdots$	$\cdots$
	34.9-24.0″ NE	2.9×10^{-17}	57	$\cdots$	$\cdots$
	21.1-10.9″ NE	3.3×10^{-17}	78	$\cdots$	$\cdots$
	7.8-15.3″ SW	2.3×10^{-17}	46	$\cdots$	$\cdots$
	29.9-48.5″ SW	2.5×10^{-17}	50	$\cdots$	$\cdots$
	65.1-94.7″ SW	1.2×10^{-17}	60	$\cdots$	$\cdots$
	94.8-150.6″ SW	6.7×10^{-18}	41	$\cdots$	$\cdots$
	NE sum[a]	1.7×10^{-17}	53	0.14	0.66
	SW sum[a]	1.2×10^{-17}	56	0.19	0.67

Note. — 1) Col. 2—aperture is listed as the offset from the nucleus in arcseconds (the slit is 2″ wide); Col. 3—The surface brightness of Hα emission line in erg s^{-1} cm^{-2} arcsecond^{-2}; Col. 4—FWHM in km s^{-1} of Hα line (in the case that EQW(Hα) > 3Å) and [NII]6583 (in the case that EQW(Hα) < 3Å) after correction for the instrumental resolution; Col. 5 & 6—[NII]λ6583/Hα and [SII]λ6716+λ6731/Hα respectively. 2) The effect of the stellar Hα absorption has been corrected (see text for details).

[a]'NE sum'—the listed apertures NE of the nucleus were summed to measure the [NII] and [SII] emission lines, due to the weakness of these lines in the spectrum; 'SW sum'—similarly the listed apertures SW of the nucleus were summed.

Table 4.   Emission-line Properties of DIM Part II. [OIII] and [OI]

Object	Aperture	$\Sigma_{\mathrm{[OIII]5007}}$[a] (erg s^{-1} cm^{-2} arcsec^{-2})	$\Delta V_{\mathrm{[OIII]5007}}$[b] (km s^{-1})	[OIII]5007/Hβ[c]	[OI]6300/Hα[d]
M 51	sum NE[e]	1.4×10^{-17}	180	2	$\cdots$
	sum SW[f]	7.6×10^{-18}	130	1.5	$\cdots$
	46.9-62.0″ SW	5.9×10^{-18}	100	1	$\cdots$
	$\cdots$ [d]	$\cdots$	$\cdots$	$\cdots$	0.1(marginal)
M 101	144.8-140.0″+ 135.5-120.3″ SE	$<2.4\times10^{-18}$	$\cdots$	<0.2	$\cdots$
	77.2-66.2″+ 63.8-61.0″ SE	7.2×10^{-18}	130	0.3	$\cdots$
	53.7-46.2″+ 42.4-41.0″ SE	$<4.7\times10^{-18}$	$\cdots$	<0.4	$\cdots$
	22.2-28.3″ NW	1.3×10^{-17}	130	0.6	$\cdots$
	35.3-45.6″+ 49.4-56.3″ NW	8.1×10^{-18}	110	0.4	$\cdots$
	80.2-84.2″ NW	8.0×10^{-18}	50	0.7	$\cdots$
	$\cdots$ [d]	$\cdots$	$\cdots$	$\cdots$	0.1(marginal)
NGC 2403	145.1-130.0″ NE	1.6×10^{-17}	100	1.5	$\cdots$
	130.0-119.7″ NE	1.7×10^{-17}	50	1.4	$\cdots$
	74.8-67.3″ NE	1.5×10^{-17}	170	1.0	$\cdots$
	67.2-59.7″ NE	1.3×10^{-17}	160	1.0	$\cdots$
	87.4-151.5″ SW	3.6×10^{-18}	60	0.65	$\cdots$
	$\cdots$ [d]	$\cdots$	$\cdots$	$\cdots$	0.2
NGC 4395	34.9-24.0″ NE	7.7×10^{-18}	<40	0.7	$\cdots$
	nearnuc sum [g]	1.5×10^{-17}	170	2.4	$\cdots$
	29.9-48.5″ SW	$<3.2\times10^{-18}$	$\cdots$	<0.4	$\cdots$

Table 4—Continued

Object	Aperture	$\Sigma_{[OIII]5007}$[a] (erg s^{-1} cm^{-2} arcsec^{-2})	$\Delta V_{[OIII]5007}$[b] (km s^{-1})	[OIII]5007/Hβ[c]	[OI]6300/Hα[d]

Note. — 1) Most apertures listed in Col. 2 are defined in the same way as in Table 3. Apertures were selectively summed as necessary to achieve the best S/N ratio. Some apertures associated with very noisy spectra were not used. 2) The effect of the stellar Hα absorption has been corrected (see text for details).

[a][OIII]λ5007 line surface brightness in units of erg s^{-1} cm^{-2} arcsecond^{-2}. In the regions where the line is not detected, upper limits are given which are estimated using 5 σ of background.

[b]Deconvolved line width of [OIII]λ5007 in km/s. In the regions where the line is not resolved, upper limits are given which are estimated using the instrument resolution.

[c][OIII]λ5007/Hβ ratios. In the regions where the [OIII]λ5007 line is not detected, upper limits are given which are estimated using 5 σ of background for [OIII]λ5007.

[d]The apertures used to measure [OI]λ6300 line for M51 and M101 are the sum of the individual apertures listed in Table 3. For NGC2403 the apertures 134.1-119.7$''$ NE and 87.4-122.5$''$ SW were summed. The [OI]λ6300 line is blended with night sky lines in M81 and NGC4395 spectra and was thus not measurable.

[e]The apertures summed are 92.5-90.5$''$ NE, 84.9-80.8$''$ NE and 63.5-52.6$''$ NE.

[f]The apertures summed are 95.2-102.0$''$ SW, 105.5-107.5$''$ SW and 117.3-152.4$''$ SW.

[g]The aperture summed are 21.1-10.9$''$ NE and 7.8-15.3$''$ SW. Note that NGC 4395 has a Seyfert nucleus, which may affect the [OIII]/Hβ ratio and [OIII]5007 line width.

Table 5.   DIM Imaging Result[a]

Object	Hα Flux (erg s^{-1} cm^{-2})	$L_{H\alpha}$ (L$\odot$)	Mean $\Sigma_{H\alpha}$[b] (pc cm^{-6})	Mean/r.m.s.[c]	Σ_{50}[d] (pc cm^{-6})
M 51	2.0×10^{-11}	4.4×10^{7}	35	0.24	400
M 81	3.2×10^{-11}	1.3×10^{7}	16	0.30	74
M 101	3.7×10^{-11}	6.3×10^{7}	9.5	0.12	230
NGC 2403	3.3×10^{-11}	1.1×10^{7}	19	0.19	230
NGC 4395	9.2×10^{-12}	1.9×10^{6}	9.2	0.24	74

[a]Correction for foreground Galactic extinction has not been applied to the data in this table.

[b]Mean Hα surface brightness within the galaxy's B = 25 mag arcsec^{-2} isophote converted to emission measure assuming an electron temperature of 10^4 K (5×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2} corresponds to 25 pc cm^{-6}).

[c]The ratio of mean to r.m.s of Hα surface brightness.   This ratio is used to characterize the 'DIMness' of a galaxy. See text for more details.

[d]Hα surface brightness level at which fainter gas contributes 50% of total Hα flux. The unit is converted to that of emission measure assuming an electron temperature of 10^4 K.

Table 6.   Observed Typical Emission Line Ratios of the DIM

Object	[NII]λ6583/Hα	[SII]λ6717/Hα[a]	[OI]λ6300/Hα[b]	[OIII]λ5007/Hβ
M 51	1.2; 0.44	0.47; 0.11	0.1(*); 0.015	1; 0.4
M 81	1.6; 0.53	1.1; 0.43	...	...
M 101	0.64; 0.26	0.36; 0.13	0.1(*); 0.012	0.4; 0.1
NGC 2403	0.29; 0.28	0.45; 0.21	0.2; 0.030	1.0; 0.4
NGC 4395	0.19; 0.11	0.42; 0.14	...	0.6; 2
Galaxy[c]	0.3; $\cdots$	0.35; $\cdots$	<0.02; $\cdots$	<0.2; $\cdots$
NGC 891 reg. 1[d]	0.6-1.1; $\cdots$	0.3-0.6; $\cdots$	<0.05; $\cdots$	<0.4; $\cdots$
NGC 891 reg. 2[d]	0.4-0.8; $\cdots$	0.25-0.35; $\cdots$	$\cdots$	$\cdots$

Note. — Listed line-ratios are from averaged DIM and HII region spectra. Semi-colon separated values are for the DIM and HII regions respectively; For the Galaxy and NGC 891 only the DIM line-ratios are given.

[a] [SII]λ6731 is not included in order to compare to the data of the Milky Way and NGC 891. Including this line would increase the ratios by a factor $\simeq$1.7.

[b] Ratios marked with (*) are calculated from the marginally detected [OI]λ6300 line flux.

[c] From Reynolds 1990, 1991.

[d] From Dettmar 1992.

Table 7.   DIM Scale-Heights

Object	Σ_*[a] $(M_\odot \ pc^{-2})$	$\Delta V_{\mathtt{H}\alpha,\mathtt{NII}}$[b] $(km \ s^{-1})$	$H_{\mathtt{H}\alpha,\mathtt{NII}}$[c] (pc)	$\Delta V_{\mathtt{OIII5007}}$[d] $(km \ s^{-1})$	$H_{\mathtt{OIII5007}}$[e] (pc)
M 51	200	80-100	470-620	110-170	700-1300
M 81	150	60-150	400-1300	$\cdots$	$\cdots$
M 101	340	30-90	120-400	60-120	250-560
NGC 2403	250	50-60	240-300	60-160	300-1000
NGC 4395	94	40-60	330-530	$\cdots$	$\cdots$

Table 7—Continued

Object	$\Sigma_*{}^{\mathrm{a}}$	$\Delta V_{\mathrm{H}\alpha,\mathrm{NII}}{}^{\mathrm{b}}$	$\mathrm{H}_{\mathrm{H}\alpha,\mathrm{NII}}{}^{\mathrm{c}}$	$\Delta V_{\mathrm{OIII5007}}{}^{\mathrm{d}}$	$\mathrm{H}_{\mathrm{OIII5007}}{}^{\mathrm{e}}$
	($M_\odot$ pc^{-2})	(km s^{-1})	(pc)	(km s^{-1})	(pc)

[a]Surface density of stellar mass within the central $5'$ regions of the galaxies that are covered by our spectroscopic observations. These values are estimated from V- and B-band surface photometry measurements by Okamura et al. (1976)(M 51 and M 101), Brandt et al. (1972) (M 81), Bothun & Rogers (1992) (NGC 2403) and van der Kruit (1987) (NGC 4395). A correction for inclination has been applied and a mass-to-light ratio of 5 times the solar value in both bands has been adopted in this calculation.

[b]The range of the FWHMs of the DIM emission lines Hα (for cases in which the Hα equivalent width EQW(Hα) is larger than $3\AA$) and [NII]6583 (when the EQW(Hα) is less than $3\AA$). The observed values are equated to those in the z direction by assuming isotropic motion of the gas.

[c]Scale height of the diffuse gas corresponding to the FWHMs of the Hα and [NII] lines, calculated assuming an exponential distribution of mass in the z direction with a scale height of 350 pc. See text for further details.

[d]The range of the FWHM of the DIM emission line [OIII]λ5007. The observed values are equated to those in the z direction by assuming isotropic motion of the gas.

[e]Scale height of the diffuse gas corresponding to the FWHMs of the [OIII]λ5007 line, calculated assuming an exponential distribution of mass in the z direction with a scale height of 350 pc. See text for further details.

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